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Remote-Controlled Rotorcraft Blade Vibration and Modal Analysis at Low Frequencies

by Natasha C Bradley

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14. ABSTRACT

Health and usage monitoring systems (HUMSs) collect sensor data from vehicle mechanical systems, subsystems, and components to address issues related to safety, maintenance, and reliability of vehicles. The US Army encourages open HUMS architectures. A typical HUMS box collects data during flight and stores the data for further analysis to determine the current state, reliability, and safety of the vehicle. This HUMS study collects sensor data on a blade removed from a remote-controlled rotorcraft as a surrogate for a full-size rotorcraft blade. This report explains the outcome of the study and details how HUMs data can be collected on rotorcraft blades. This report will also demonstrate that accelerometers can be used to ascertain the natural frequencies of these blades, such that vibratory testing can be controlled and used to ultimately determine if the blade damage, wear, age, etc. has a measurable effect on frequency response.

15. SUBJECT TERMS

blade, vibration analysis, modal analysis, remote-controlled helicopter, remote-controlled rotorcraft, HUMS for rotorcraft

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1. Introduction

Health and usage monitoring systems (HUMSs) collect sensor data from vehicle mechanical systems, subsystems, and components to address issues related to safety, maintenance, and reliability of vehicles. The US Army encourages open HUMS architectures. The rotorcraft blade is a critical component and candidate for the HUMS capability assessment for innovation. This memorandum report explains how HUMs data can be collected on rotorcraft blades. Acquiring knowledge of the blades' natural frequency is a prerequisite to understanding the health and usage monitoring of the blade under real operating condition. Ultimately, a HUMS for the blade would perform vibratory signal analysis on the blade and use the results of this analysis to assess real-time health and early detection of incipient flaws in the blade. This could potentially allow for operators to quickly address and fix problems before they grow and cause collateral damage to the rotorcraft.

2. Background

A typical HUMS box collects data for the purpose of detecting impending mechanical failures. The system collects data during flight and stores the data for further analysis. HUMSs provide some degrees of health status of rotorcraft systems, subsystems, and components via data analysis using ground-based stations. HUMS analysis is performed to provide condition indicators of the current health and safety of the vehicle. This study used a blade from a remote-controlled rotorcraft as a surrogate for a full-size rotorcraft blade.

3. Experimental Setup

In this experiment, the rotor blade was attached to a mechanical shaker using a blade grip (Fig. 1). The blade was oriented horizontally (x-y plane), and the shaker was pulsing in the vertical direction (z axis). The exact composition of the blade material, an aluminum alloy, was unknown because the manufacturer considers that information proprietary. The blade was in the shape of an airfoil 2.5 inches wide, 34.5 inches long, and 0.224 inch thick at the leading edge.

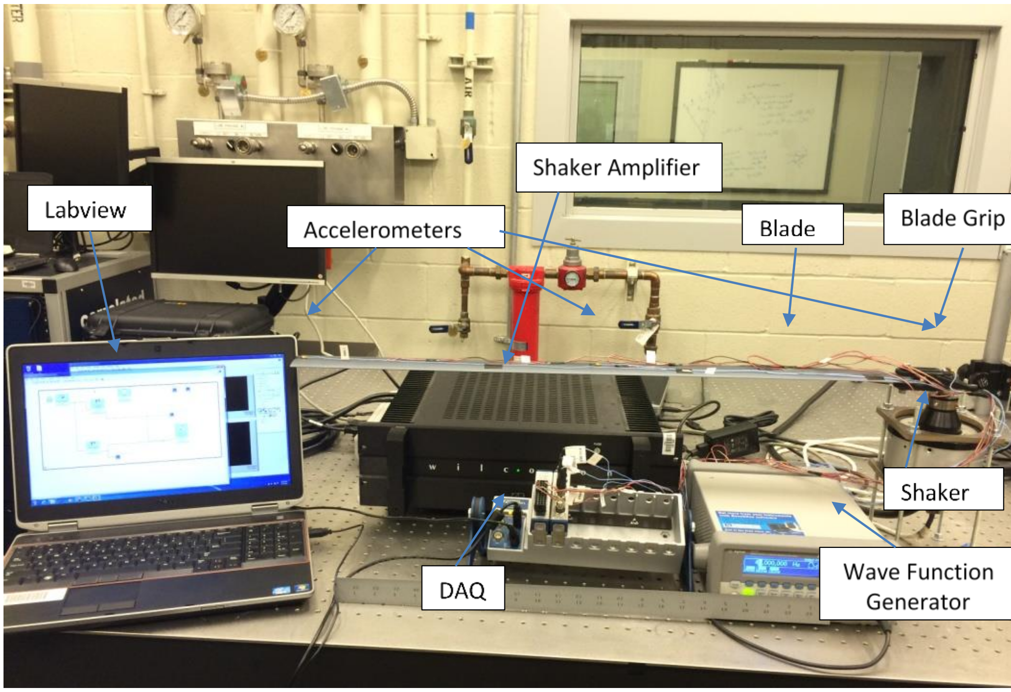

Fig. 1   Laboratory Virtual Instrument Engineering Workbench (LabVIEW) test setup

Accelerometers and strain gages were attached to the surface of the blade, transmitting vibration and strain information to the data acquisition unit (DAQ, National Instruments) (Fig. 1). The vibration and strain data were used to capture exactly what would happen to the rotor blade over different frequencies. This information would allow us to assign a health value (health index) to the rotor blade over time and thus be able to assign baseline and threshold usage values that could later be used to establish guidelines for normal and extreme usages. Once the normal and extreme usage threshold values were identified, we could begin to test flawed rotor blades in the same manner that the unflawed rotor blade was tested.

Frequency, amplitude, and mode data of vibration were collected while the shaker was outputting a sine wave, the frequency of which was varied in a controlled fashion. The analysis of this data could be used to define the baseline health of the blade.

The equipment used in this experiment was a Wilcoxon Megget F4/F7 electromagnetic and piezoelectric shaker system including an F4 electromagnetic shaker, F7 piezoelectric shaker with an integral impedance head, and Wilcoxon power amplifier. An Agilent wave-function generator provided the signal to the power amplifier. In addition, a laptop equipped with LabVIEW software was attached to the specimen and used to record accelerometer and strain gage data over time. Single-axis accelerometers were used to measure vibration data. The reason for using single-axis accelerometers instead of triaxis accelerometers was that the

test specimen could only be moved in the z direction, so the vibration data collected in the other directions would be small and irrelevant (at least this was the assumption; if invalid, it might explain some of the discrepancies in the measured versus predicted results). To collect the modal data, a Hewlett-Packard dynamic signal analyzer replaced the wave-function generator, DAQ, and LabVIEW (Fig. 2). A PCB piezotronics miniature instrumented impact hammer was used as an excitation source to collect modal data (Fig. 3). The Table shows the test type and accelerometer locations.

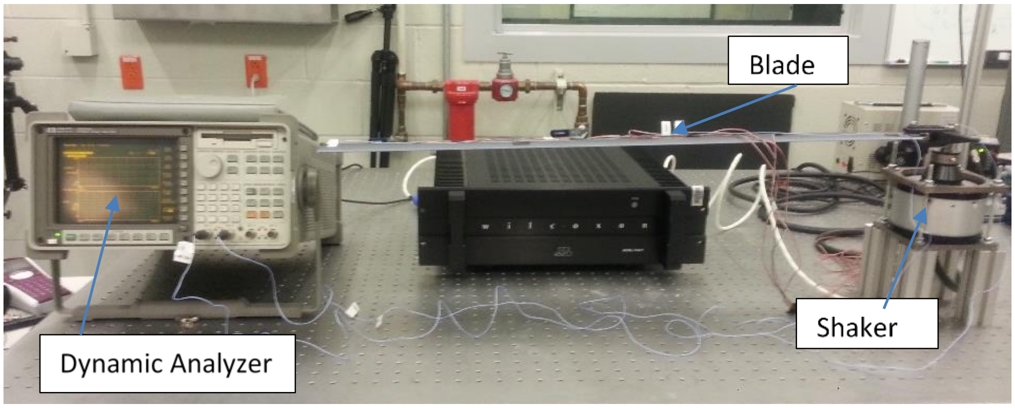

Fig. 2 Shaker test setup for model analysis

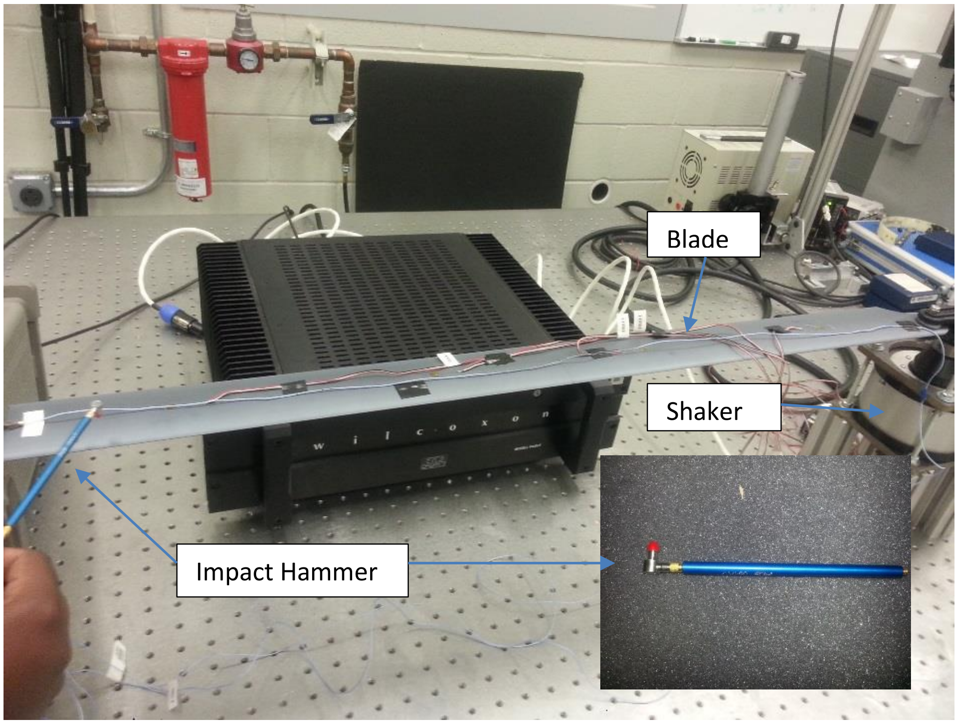

Fig. 3 Impact hammer test setup

Table Accelerometer location (l) relative to total blade length (L)

Test	Accelerometer tip location (l/L) (inches)	Accelerometer midpoint location (l/L) (inches)	Accelerometer shaker (l/L) (inches)
LabVIEW baseline data collection	1 ± 0.06	0.5 ± 0.06	–0.04 ± 0.06
Impact hammer modal analysis	1 ± 0.06	0.5 ± 0.06	–0.04 ± 0.06
Dynamic analyzer modal analysis	1 ± 0.06	0.5 ± 0.06	–0.04 ± 0.06

4. Results

4.1 Rotor Blade Acceleration

The baseline data was collected by both accelerometers and strain gauges. This memorandum report will focus on the accelerometer results. In Fig. 4, a 5-Hz sine wave was input to the blade by the shaker. The blade itself showed a response where the tip was out of phase with the excitation point. As will be discussed later in this report, this result is puzzling because at such a low frequency (under the predicted first mode natural frequency) the tip and midpoint of the blade should have been in phase with the shaker. The midpoint of the blade was also reaching a much higher acceleration than the tip, which was only true after you passed the first mode natural frequency.

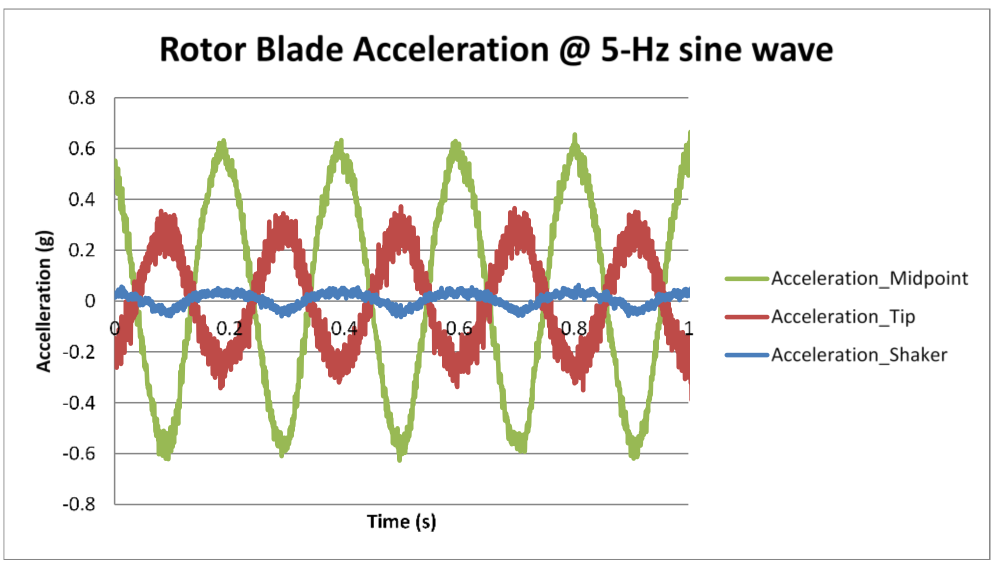

Fig. 4 Blade response to shaker outputting 1-V sine wave at 5 Hz

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Figure 5 depicts a 100-Hz sine wave where the tip excitation was clearly larger than the acceleration recorded at the midpoint. The tip and the midpoint were also out of phase with the shaker acceleration. These observations make a case for the blade to be above the third mode.

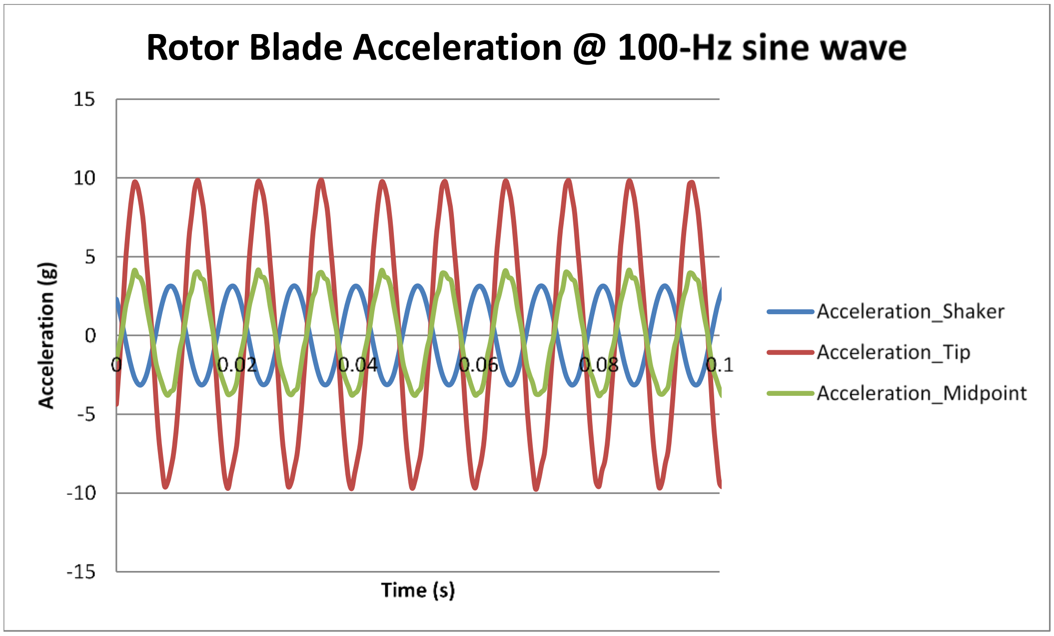

Fig. 5   Rotor blade response to shaker outputting 1-V sine wave at 100 Hz

Figure 6, depicting the 20- to 100-Hz sine sweep, shows an interesting pattern with the acceleration of the shaker. The shaker was showing a change in amplitude as it was swept from 20–100 Hz in 1 s; at approximately 0.3 s or approximately 40 Hz (assuming a constant sweep rate) the shaker amplitude peaks. To investigate this peaking phenomenon, the output of the shaker itself (without blade) was tested.

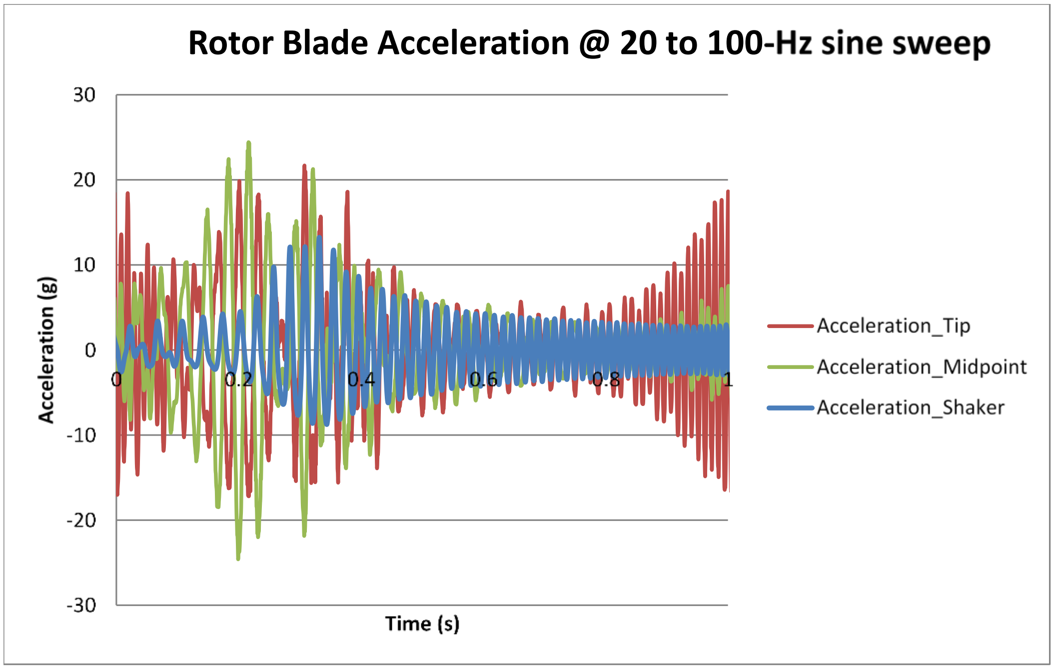

Fig. 6 Rotor blade response to shaker outputting 1-V sine sweep from 20- to 100-Hz duration of 1 s

Figure 7 shows the shaker output at different frequencies between 5 and 100 Hz. The shaker shook much harder around 40 Hz, which indicated the possibility of a natural frequency of the shaker occurring around 40 Hz, and thus explained the point of maximum shaker amplitude in Fig. 6.

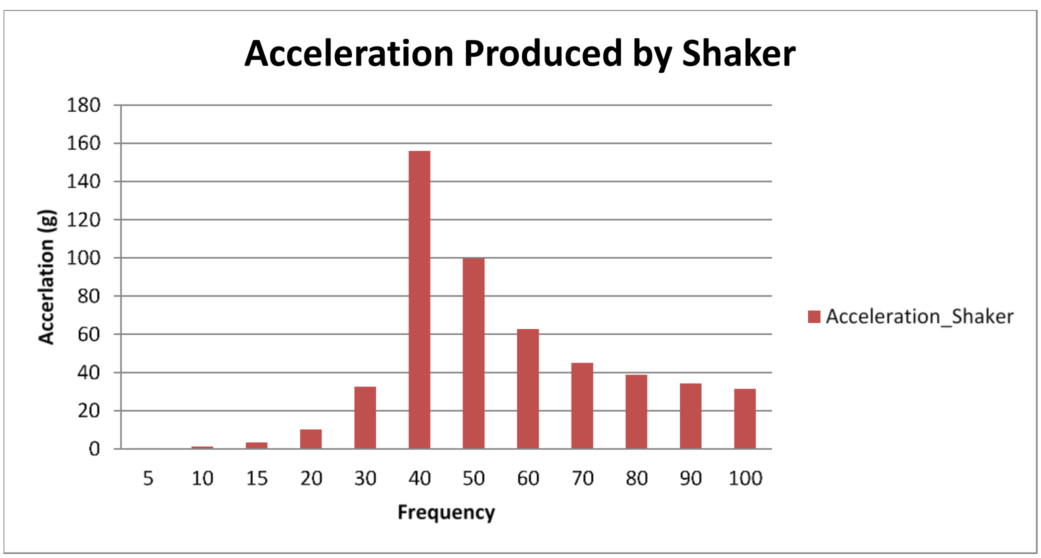

Fig. 7 Acceleration produced by shaker with no attachment

4.2 Modal Analysis: Using an Impact Hammer

A modal analysis was performed to locate the first 3 modes within the blade so that when testing occurred the frequencies chosen were not natural frequencies. This is important because when an object is vibrated at the same frequency as its natural frequency, the object can be seriously damaged or even cause damage to any object near it. On the other hand, if a modal analysis indicated that the natural frequency had changed from the baseline, it could be an indication of blade damage. Testing was performed with the dynamic analyzer and the impact hammer. The analyzed data were input into a MATLAB program to calculate mode shapes; mode 1 was found at 31 Hz; mode 2 was found at 95 Hz; and mode 3 was found at 183 Hz, as seen in Fig. 8. Although this blade was not a simple cantilever beam, Fig. 9 shows the approximate mode shapes. As stated earlier, the results of Figs. 4 and 5 indicated that the first mode shape was lower than 20 Hz and the third mode shape was lower than 100 Hz. Thus, the data from Figs. 4 and 5 are inconsistent with the data in Fig. 8, and the analysis was revised accordingly.

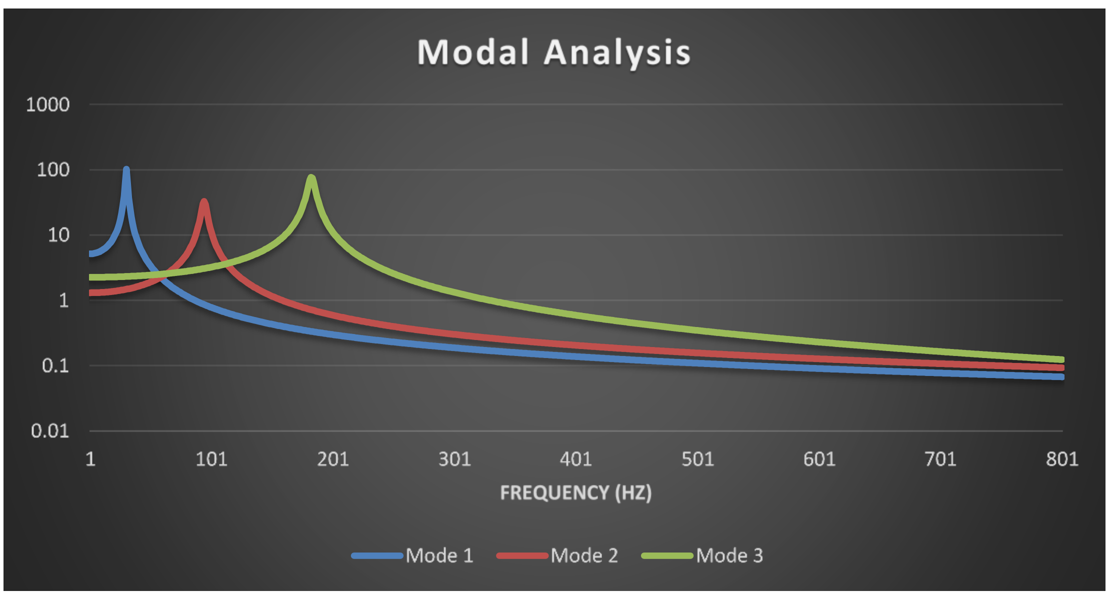

Fig. 8 First 3 modes observed using force caused by impact hammer

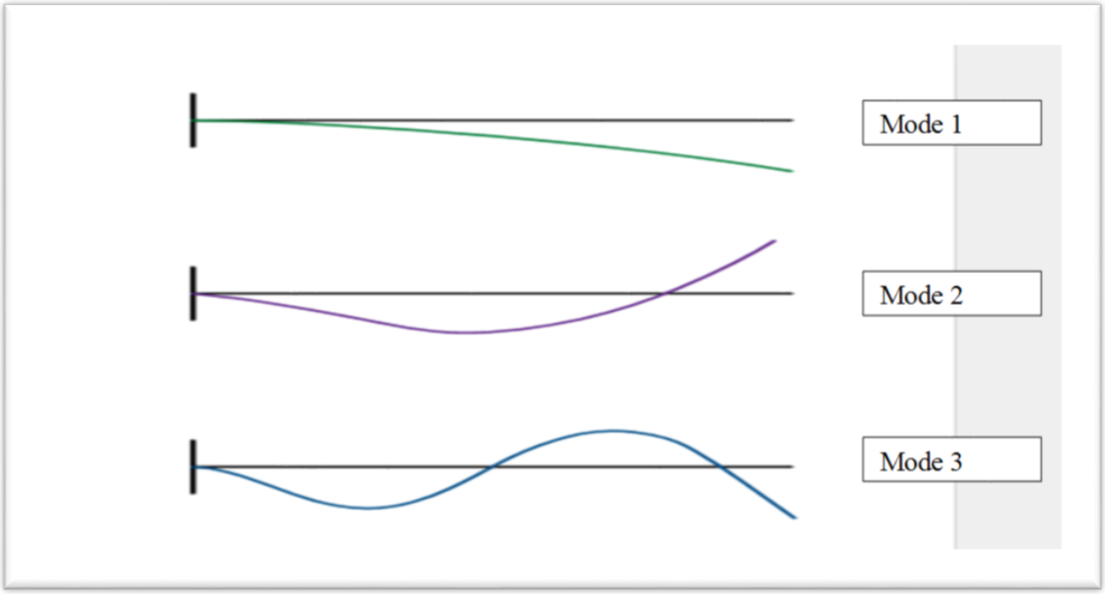

Fig. 9 Standard mode shapes for cantilever beam

4.3 Dynamic Response Revisited

A complete dynamic response was graphed for the results from the impact hammer test (Fig. 10) as well as the results from a dynamic response test with the shaker (Fig. 11). The impact hammer involved an initial hit. Originally, this event was assumed to be the origin of the peak at 4 Hz in Fig. 10 and for this reason was not entered in to the MATLAB modal analysis algorithm. However, in hindsight, a small-amplitude bump (previously ignored as "noise") also appeared near 4 Hz in the shaker driven amplitude response of Fig. 11 (no impact hammer involved). If the amplitude at 4 Hz was indeed the first-mode response, that would shift the second mode to 31 Hz and the third mode to 95 Hz (and the fourth mode to 183 Hz), removing the previous inconsistency among Figs. 4, 5, and 8.

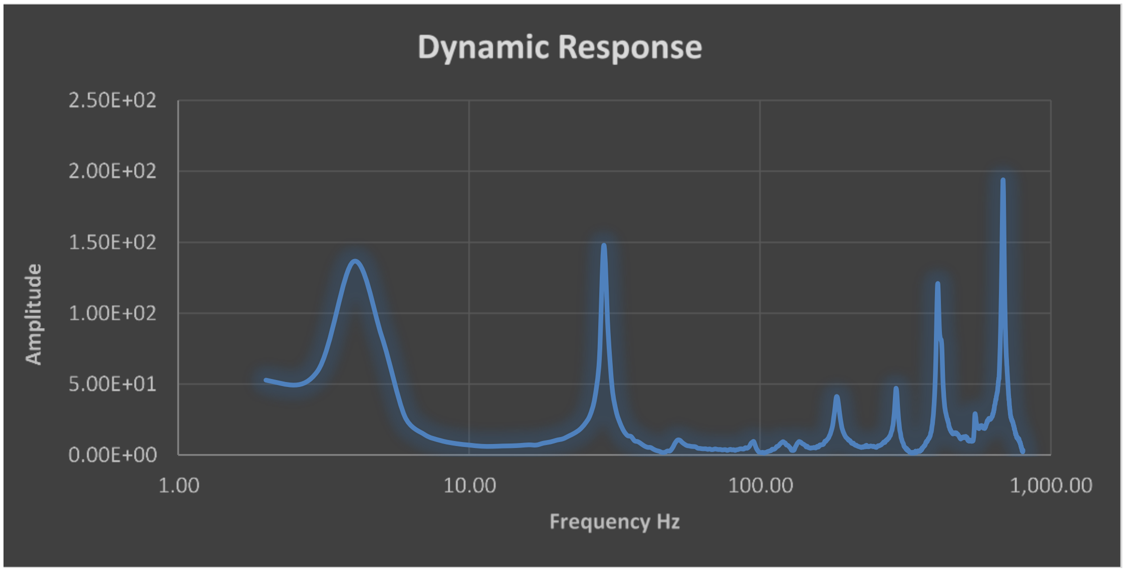

Fig. 10 Dynamic frequency response using impact hammer

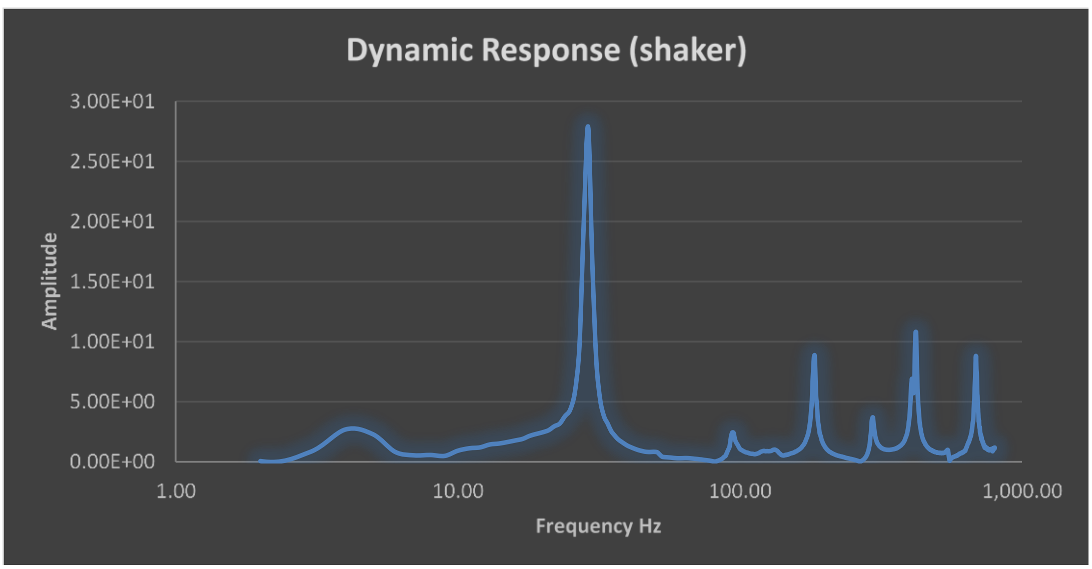

Fig. 11 Dynamic frequency response using shaker

5. Conclusion

This study was successful in demonstrating that accelerometers could be used to ascertain the natural frequencies of these rotorcraft blades such that vibratory testing could be controlled and used to ultimately study how the blade damage, wear, age, etc. might or might not have a measurable effect on frequency response. The data analysis favors the conclusion that this particular rotor blade has a mode-1 natural frequency near 4 Hz, mode-2 natural frequency near 31 Hz, mode-3 natural frequency near 95 Hz, and mode-4 natural frequency near 183 Hz. Future testing with biaxial or triaxial accelerometers, with better sensitivity at lower frequencies (<5 Hz for this blade), would substantiate the correctness or incorrectness of assumptions made in this study. For instance, a biaxial accelerometer also could be used to explore the possibilities of torsional forces having an impact on the modal frequencies. In addition, the blade can also be analyzed with computer-aided engineering (CAE) tools, solid modeling, and finite element analysis. The use of CAE with modal testing may help determine the origin of blade damage. Collecting data in this fashion will enable us to monitor systems using vibration measurements and perform analysis to determine the current state of the system.

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